OUR BEST FRIEND, THE COMA CLUSTER (A HISTORICAL REVIEW)

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In this paper I describe how our knowledge and understanding of the properties and structure of the Coma cluster of galaxies has evolved through the years, since early this century, when the first maps of the density of nebulæ in the Coma region were produced, and until the present time. It is shown that most of the recent discoveries that have led to a change in our view of this cluster, were in fact anticipated very early on.

1 Introduction: Why Coma?

Coma is one of the most studied clusters of galaxies of the sky, along with Virgo and Perseus[a]. While being the most distant of the three, with a mean redshift $z \simeq 0.23$, Coma has also been the most appealing to observers because of its location near the galactic pole (bII= 88°) and because of its richness[b].

Another characteristic that differentiates Coma from Virgo and Perseus is its regular and (roughly) spherical shape. In Shane & Wirtanen[122]'s words:

> *There appear to be two extreme structural types among the populous clusters, exemplified by the Virgo and the Coma clusters. The Virgo type is characterized by the absence of a strong central condensation and by lack of symmetry [...] The Coma-type cluster is characterized by a strong central condensation and a tendency towards spherical symmetry.*

What could be more charming than spherical symmetry (even if only approximate, see e.g. Schipper & King[119]) for a theoretician? It is indeed not surprising that Coma has been chosen as the prototype cluster by theoreticians, since the early papers of Zwicky[163,164] and others (e.g. Carpenter[25], Holmberg[70], Tuberg[141]), and until the recent estimates of the density of matter in the Universe (e.g. the "baryon catastrophe" of Briel et al.[19]) and recent

[a] Of the three clusters, Perseus was never dedicated a whole conference, while it was the case for Virgo[148] and Coma (these proceedings).
[b] Of the nearby clusters (distance class $\leq$ 1) only five are as rich or richer than Coma (according to Abell et al.[6]).

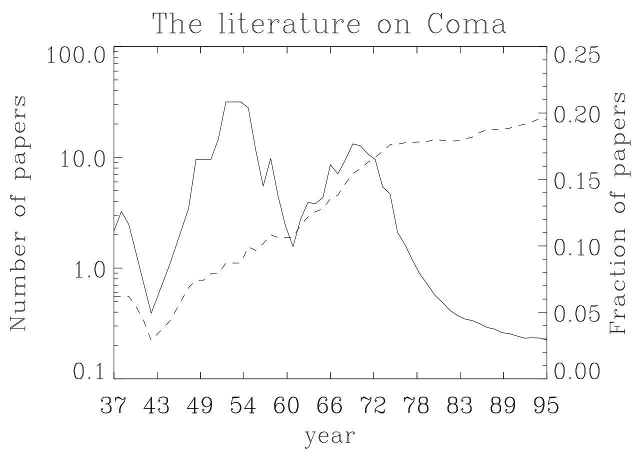

Figure 1: The number of papers published on the Coma cluster through the years (dashed line), and the ratio between the number of papers published on Coma and the number of papers published on galaxy clusters in general (solid line).

scenarios for the structure formation (e.g. the "filament" scenario of West et al.[154]).

Nevertheless, Coma's richness and regularity are not typical of all clusters. As Kent & Gunn[78] pointed out:

> *Coma is quite atypical among clusters in its richness, compactness, and degree of symmetry.*

On the other hand, the title of this conference indicates that we now have "a new vision" of Coma, that emerged through the (once controversial) works of many people (e.g. Fitchett & Webster[47], Mellier et al.[93]). As Biviano et al.[16] wrote:

> *Coma can now be considered as the prototype of rich clusters endowed with subclusters, and thus not fully relaxed*

The interest of the astronomical community in Coma can be traced by counting the number of publications dealing with this cluster, through the years. While the total number of publications on Coma has continuously increased with time (Fig.1), the increase rate diminished in the 70's, when Coma became one of many well-studied clusters. This can be also seen by plotting the same number divided by the number of publications on galaxy clusters in

general (Fig.1): there is a continuously decreasing trend from the 70's on. No doubt the proceedings of this conference will mark a change in this trend!

In the next sections I will describe how our vision of Coma has evolved through the years[c]. For topics not covered in this review, I refer the reader to the contributions of Feretti, Gavazzi, Jones, and West in these same proceedings.

2 Coma: an Old Friend

2.1 The Myth

The origin of the name "Coma Berenices" dates back to the year $\sim$ 245 B.C, when Ptolemy III, the Egypt pharaon, left his country to make war against Syria. His wife, Berenices, worried for her husband's safety, offered a lock of her hairs to the goddess Arsinœs Zephiritis in the temple of Canōpus (near today's Abūqīr).

The lock misteriously disappeared during the night, and princess Berenices felt very sad about what she considered a bad omen. Conon, the court astronomer, told the princess that the lock had been transformed into a star constellation, *Coma Berenices,* i.e. Berenices' hairs.

Apparently, the goddess appreciated Berenices' offer, infact Ptolemy came back safe. Berenices had a pleasant and rich life until she was killed by one of her sons.

It was not until 1629 that the constellation name was used again, by Kepler.

2.2 The Coma cluster of nebulæ

In historic times, Herschel[69] was the first to notice the concentration of nebulæ in the constellation of Coma Berenices. A more rigorous catalogation of nebulæ in the Coma region was done by Wolf[159,160] in the early years of this century (following up an earlier work of D'Arrest[32]). Wolf counted 108 nebulæ in a circle of 30' diameter. The number of catalogued nebulæ in the Coma region increased to more than 300 with the observations of Curtis[31]. Wolf's map of the density of nebulæ in the Coma region (see Fig.2), already shows the elongated shape of the cluster in the south-west direction, where a secondary density concentration appears to lie (the south-west subcluster, see § 7.1).

[c] I have stopped my historical review with the year 1995. More recent works are cited only occasionally (with a possible bias towards my owns!).

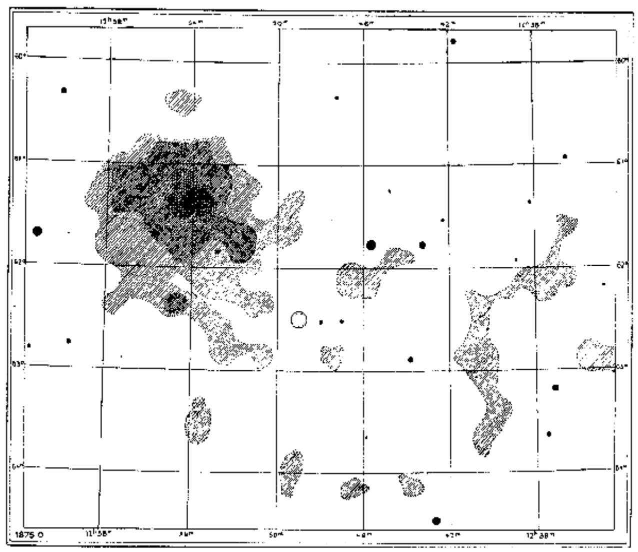

Figure 2: The density of nebulae in the region of Coma, according to Wolf. Note the south-western extension (north is up, east is to the left). Every grid element is 28'×60'.

Hubble & Humason[71] first measured the velocities of a few cluster nebulæ, ranging from 5100 km/s to 8500 km/s (an interval quite close to the real full extension of Coma in velocity space – see, e.g. Gavazzi et al.[54]).

3 Weighing Coma

3.1 Zwicky's Heresy

The mass of Coma was first estimated by Zwicky[162,163] to be[d] $M > 5 \times 10^{14} M_\odot$, using the virial theorem. This estimation was based on a value[165] of 1200 km/s for the radial velocity dispersion of the cluster galaxies, σ_v, not too far from current estimates (e.g. Colless & Dunn[27]).

The corresponding mass-to-light ratio was large, $M/L > 50 M_\odot / L_\odot$, and a form of unvisible matter seemed needed. Zwicky suggested that this dark matter could be detected as diffuse IC light.

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[d] Throughout this paper I use $H_0 = 50$ km/s/Mpc, and scale all H_0-dependent quantities accordingly. Note that the recent measurement of the Sunyaev-Zel'dovich effect in Coma (Herbig et al.[68]) implies $H_0 = 71^{+30}_{-25}$ km/s/Mpc, consistent with the value adopted here.

Zwicky's hypothesis of some form of dark matter dominating the cluster dynamics, was not accepted by his contemporaries. Holmberg[70] considered it *"an unlikely assumption",* and his scepticism was still shared by the Burbidges[20] and de Vaucouleurs[36] 20 years later! However, the alternative hypothesis, clusters being unbound and expanding systems, would imply a very short timescale for disruption. This was found to be incompatible with the large number of galaxy clusters in the sky, and the similarity of nearby and distant ($z \simeq 0.2$) clusters (Zwicky[169], Limber[85]).

Had Zwicky grossly overestimated the total cluster mass? Zwicky[165] himself pointed out that the application of the virial theorem may be of only limited validity when the system has an irregular distribution of galaxies, implicitely questioning the results obtained by Smith[126] on the Virgo cluster, and anticipating recent results on clusters affected by substructures. The problem of outliers in the velocity distribution was first considered by Schwarschild[120]. The lower limit he set to the velocity dispersion of Coma, $\sigma_v > 630$ km/s, was still too high to get rid of the dark matter problem.

3.2 More Data!

A step further in the understanding of the mass and structure of Coma was done by Mayall[91], thanks to the new technology of electronic photography. In Fig.3 of his paper ~ 50 galaxy velocities are plotted vs. clustercentric distance, d, and the decrease of σ_v with d is already quite evident. Despite this significant progress, Mayall complained that:

> *...it is doubtful that satisfactory answers will be obtained until there are at least a hundred velocities available for discussion, and several hundred would be much better. If this is the case, then the current rate of less than 10 velocities per year is impracticably slow.*

It is ironic that the actual average rate since the 60's has been only twice as high[e] as the "impracticably low" rate in Mayall's times!

The first numerical simulation of the evolution of a Coma-like cluster (Peebles[106]) showed that the 3D-σ_v should decrease with increasing clustercentric distance. Nearly simultaneously, the decrease of projected-σ_v was actually measured by Rood[113] in Coma. He pointed out that such a radial trend of σ_v could be due to a real dependence of the 3D-σ_v with radius, or to an anisotropic distribution of galaxy orbits. In the early 70's Coma M/L estimates were already quite close to current estimates (see Fig.3).

[e] The total number of currently available velocities for Coma cluster galaxies is ≥ 800 (see van Haarlem's contribution in these proceedings), i.e. 750 new velocities in the last 37 years.

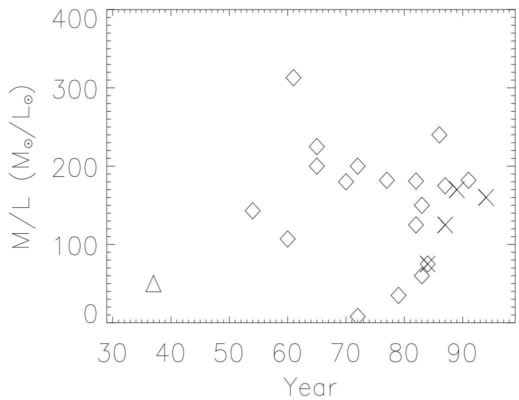

Figure 3: Several estimates of Coma M/L vs. the year when they were derived. Diamonds represent estimates based on optical data, X's represent estimates based on X-ray data; a triangle represent Zwicky's original lower limit estimate.

The density profile, accurately determined by Omer et al.[104] and Rood et al.[115], in combination with the σ_v-profile (see Fig.4), was used by Rood et al. to derive Coma's M/L, and constrain the orbital anisotropy of Coma galaxies. They came to the conclusion that the density and velocity dispersion profiles are *"consistent with an isotropic velocity distribution"*. Ivan King[81], the last author in Rood et al.'s paper, relaxed this conclusion. He noted that, in fact, several distributions of the galaxies and the dark matter were consistent with the data, and current cluster mass estimates could be systematically in error by a factor three. Ten years after, Kent & Gunn and Bailey[13] arrived at (rouhgly) the same conclusions of Rood et al. and, respectively, King!

In the following years, mainly through the observations of Gregory & Tifft[60,61,62,138], the total number of measured redshifts for Coma galaxies increased to over 200.

3.3 Beyond the Virial Theorem

With some hundreds velocities available, more detailed models became possible. A new heresy came around, the "binary model" of Valtonen & Byrd[143,144], somewhat anticipated in the works of Gainullina[51], and Wesson et al.[152,153]. Valtonen & Byrd suggested that Coma could be dymanically dominated by a tightly bound couple of galaxies (NGC 4874 – NGC 4889). Their model,

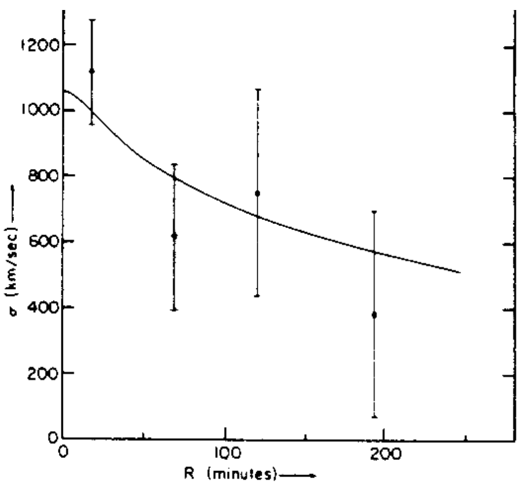

Figure 4: The radial velocity dispersion profile of Coma, km/s vs. arcminutes – from Rood et al.

while reducing the *global* dark-matter discrepancy for the cluster, nevertheless implied a very large M/L ratio for the two central dominant galaxies (~ 2000). During the last 40 years, Zwicky's heresy had become common sense; trying to reject the dark-matter hypothesis had become the new heresy! This model was rejected 10 years later, when The & White[133] showed that Valtonen & Byrd's model was inconsistent with the σ_v-profile at the centre of Coma.

Other groups followed more traditional approaches. Most (Kent & Gunn, Millington & Peach[97], The & White[130], Merritt[94]) came to the conclusions that the best-fit model is also the simplest, i.e. light traces mass, and galaxy orbits are isotropic throughout the cluster (Fuchs & Materne[49] disagreed, but their fitting method was found[97] to be very sensitive to the assumed form of the density profile). While "simplest is best" provided an adequate description of the cluster dynamics, other models could not be excluded, and the mass-to-light ratio of Coma was shown to be uncertain by a factor four (from 50 to 200 $M_\odot/L_\odot$, see Bailey). Merritt first showed that the shape of the galaxy velocity distribution at different radii contains information on the orbital anisotropy. His attempt of fitting the velocity distribution of galaxies in Coma was unsuccesful though, because of the skewness of the velocity distribution (see Fig.5). It took 9 years to understand that the skewness was caused by the contaimination of the SW group galaxy velocities (Colless & Dunn).

The X-ray observations of Gursky et al.[63] and Meekins et al.[92] showed the

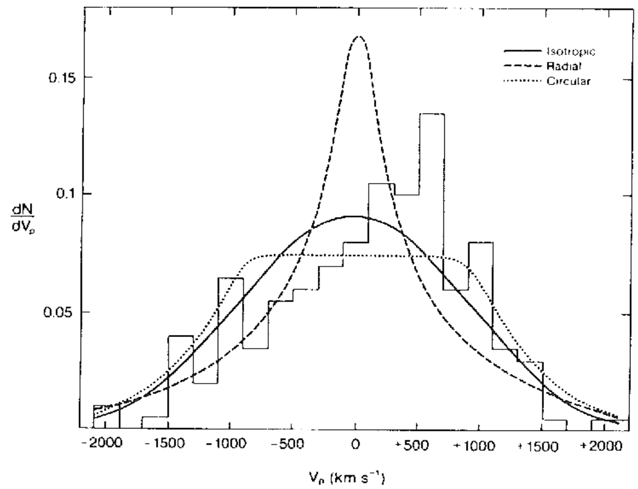

Figure 5: The observed line-of-sight distribution of the Coma galaxy velocities (in km/s) with three theoretical models superposed – from Merritt

existence of a hot IC gas component in Coma. The mass of this new component was estimated by Gursky et al. to be quite below the total cluster mass, but far from negligible.

The newly discovered IC gas mass component was taken into account in the so-called "Multi-Mass Model" of Capelato, Gerbal et al.[23,24,34,55], where they also considered a spectrum of galaxy masses. Capelato et al.[24] suggested the existence of a virialized core surrounded by a still collapsing halo. Gerbal et al.[55] were possibly the first to show that the IC gas contribution to the total mass increases with the clustercentric distance (see Fig.6).

The basic uncertainty in the X-ray based mass estimation is the ignorance of the detailed gas temperature profile. From the *HEAO 1 A-2* and OSO 8 observations in the 2-60 keV band, Henriksen & Mushotzky[67] deduced a steep gas temperature decrease with clustercentric distance. As a consequence, they revised the total cluster mass estimate downward by a factor four. Cowie et al.[29] reached a similar conclusion, by using additional data from the *Einstein IPC.*

The & White[131] criticized these results, showing that such a steep temperature decrease would require galaxies in the outer part of the cluster to be on nearly circular orbits. Based on X-ray data, Hughes et al.[72,73,74] showed that the X-ray temperature does decrease off-centre (see Fig.7), but not as steeply

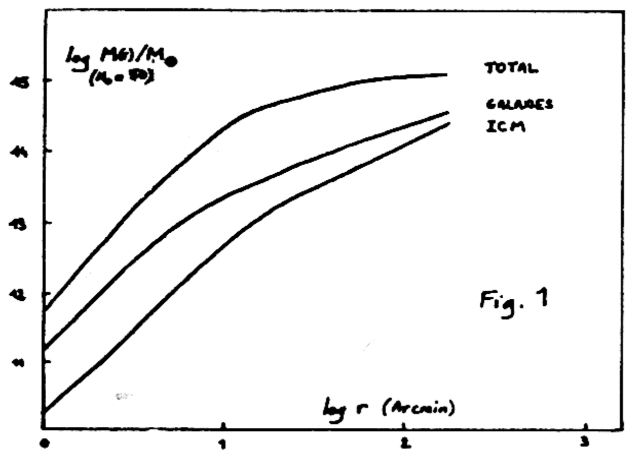

Figure 6: The mass (in solar mass units) of the various components of the Coma cluster, as a function of the clustercentric distance, in arcminutes, according to the model of Gerbal et al. (log-log plot)

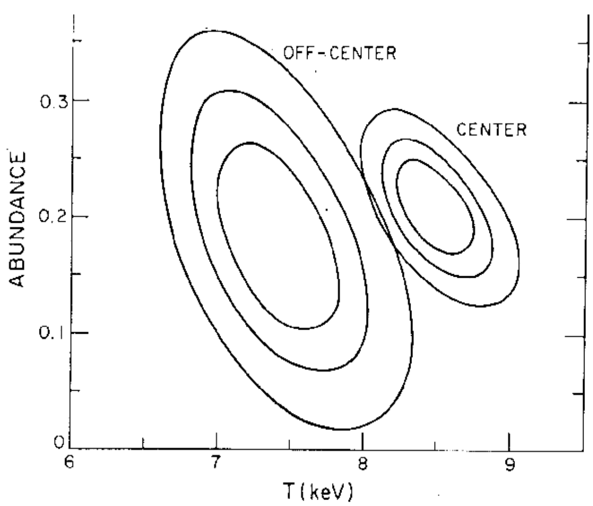

Figure 7: 2D χ^2 contours (at 68, 90 and 90 % confidence level) for the Iron abundance (with respect solar) vs. gas temperature (keV), for two pointings of *EXOSAT* - from Hughes et al.

as in Henriksen et al.'s model (which was shown to be internally inconsistent).

By combining the information from the optical and the X-ray data, Hughes et al. constrained the total mass of Coma within 1 Mpc to 3.9–$7.2\times10^{14}M_\odot$ (1.1–$3.0\times10^{15}M_\odot$ within 5 Mpc), and the mass-to-light ratio to 90–250 $M_\odot/L_\odot$. Hughes also found that the ratio of the gas mass to the total mass increases with the distance from the cluster centre, thus confirming the early suggestion of Gerbal et al., and anticipating Watt et al.[149].

Following works have not substantially modified our knowledge of the total mass and mass-to-light ratio of Coma (current estimates are $M \sim 2\times 10^{15}M_\odot$ and $M/L \sim 160M_\odot/L_\odot$, see Fusco-Femiano & Hughes[50], Makino[89], and Hughes' contribution in these proceedings). The new measures of the IC gas temperature (see Briel and Honda in these proceedings) should allow to reach even better accuracies.

4 More Light on Coma

The "missing mass" problem has always rather been a "missing light" problem. Here I review the progress done in the estimation of the luminosity function (hereafter LF) of Coma in the *optical.* Coma's LF has also been determined in several other bands, in the radio (e.g. Willson[158], Gavazzi et al.[53], Venturi et al.[146]), in the IR (Gavazzi et al.[54]), in the UV (Donas et al.[38]). Anyway, the determination of these non-optical LFs is quite recent, so I will not consider them in my review. I refer the reader to the contributions of De Propris, Gavazzi and Mobasher in these proceedings.

The first determination of the Coma LF was done by Hubble & Humason. The LF was found to peak at $m_{ph} \simeq 17$ (see Fig.8). Twenty years later, Zwicky[166] found instead

> *...that the luminosity function of the Coma cluster galaxies is monotonely increasing with decreasing brightness*

and it took eight years more for Abell[1] to show that in fact, both Hubble and Zwicky were right, since the LF of Coma has a secondary maximum at bright magnitudes (see Fig.9).

The complex form of Coma LF was known since 1959, yet since Schechter[118] proposed his analytical form for the cluster LF, any bump or irregularity in the observed LFs tended to be overlooked[f]. Many re-discoveries of this secondary maximum in the LF were needed before astronomers start recognizing that some cluster LFs are *not* well fitted by Schechter[118]'s function.

[f] This is a further proof of the skill of astronomers in fitting a straight line to a circle!

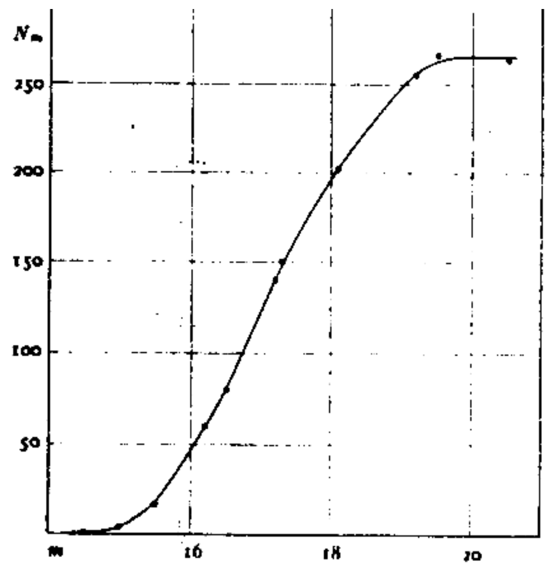

Figure 8: Cumulative counts of nebulae in the central region of Coma vs. the photographic magnitude. In this figure, magnitudes range from 14 to slightly more than 20, and counts from 0 to slightly more than 250 – from Hubble & Humason

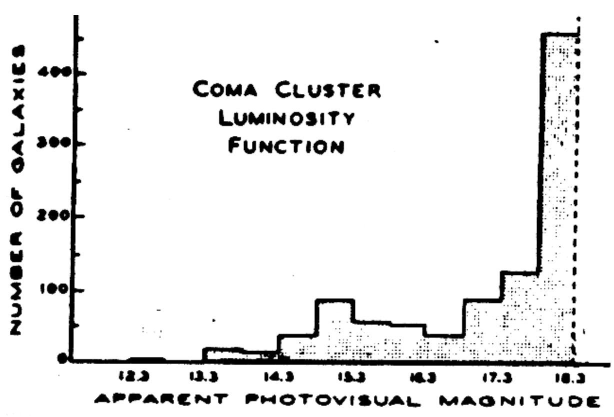

Figure 9: Differential LF of Coma galaxies. Magnitudes (on the x-axis) range from 12.3 to 18.3, counts (on the y-axis) range from 0 to 500 – from *Sky & Telescope,* **XVIII,** 495 (1959)

The first one to re-discover (or confirm) the secondary maximum was Rood[112], 10 years later; then followed Godwin & Peach[58], in the late 70's, Thompson & Gregory[135] in 1993, and finally Biviano et al.[15] who closed this issue, by using only spectroscopically confirmed cluster members from a complete galaxy sample.

New data allowed Rood[112] to show that the LF is not the same for galaxies in the inner and outer regions of Coma. The secondary maximum looked more pronounced in the LF of galaxies in the inner region, where the fraction of bright galaxies is higher. This result was confirmed by Lugger[87,88], 10 years after (despite the opposite conclusions reached by Gregory & Tifft[62]).

Numerical simulations allowed White[155] to show that dynamical friction can lead to the segregation of brighter galaxies in the cluster centre, and a modification of the inner LF. New simulations of Roos & Aarseth[117] showed that also merging can significantly affect the LF of galaxies in the centre of Coma.

The increase of Coma's LF at faint magnitudes seemed not to be strong enough to provide all the "missing light"; galaxies fainter than $m_{pv} = 18.3$ only contribute ~ 13 % of the total cluster light (Abell[4]). However, deeper observations were to indicate a further steepening of the LF. First, Abell[5] showed that at magnitudes fainter than than $m_v = 17.5$, the LF had an asymptotic slope[g] $\alpha = -1.4$. Then, using Godwin et al.[57]'s new catalogue, Metcalfe[95] determined an even steeper slope ($\alpha = -1.9$) for the LF at $b \geq 19.74$. With such a steep slope, the faint galaxy contribution to the total cluster light is significant, ~ 20 %. Metcalfe's result anticipated recent findings by Lobo et al.[86] (who find $\alpha = -1.8$; see also the contributions of Adami, Lobo, and Sekiguchi in these proceedings). Other evidences for a (more or less) steep LF at the faint end came from Karachentsev et al.[76] and Bernstein et al.[14].

5 Looking into the Dark

Observations and modelling of the Coma cluster have led theoreticians to propose and eventually discard hypotheses on the nature of dark matter. Here I review some of these hypotheses, although most are already ruled out, and maybe none will turn out to be correct.

5.1 No Dark Matter?

Zwicky's original estimate of the large mass of Coma was regarded with considerable scepticism at the beginning (see § 3.1). Possible solutions to the problem

[g] α is defined by: $N(L)\,dL \propto L^{\alpha}\,dL$

of dark matter were that Coma (and clusters in general) are unbound and expanding, or that the σ_v-estimate was boosted by the presence of interlopers. In the words of Holmberg:

> *The temporary members with their hyperbolic velocities seem to offer a more plausible solution of the difficulty.*

This solution to the problem was never totally discarded, since unidentified subclustering is known to significantly affect cluster σ_v-estimates. In the case of Coma, however, Schwarschild pointed out that interlopers cannot led to more than a factor two overestimate of the cluster σ_v. On the other hand, the instability argument could not explain why we see so many clusters, nor the apparent lack of significant evolution in the structure of clusters at different redshifts (see § 3.1).

The existence of dark matter was again questioned by Tifft[137]. He discovered a correlation between galaxy redshifts and magnitudes that led him to question the usual physical interpretation of a galaxy redshift. Tifft estimated that the intrinsic Doppler velocity dispersion could be less than 220 km/s. To my knowledge, this so-called "band-effect" has never really been ruled out (it was even recently confirmed by Nanni et al.[99]), unless Simkin[124] was right and the effect is an artefact due to night-sky distorsion in the observed spectra.

Another viable solution to the "missing mass" problem, that does not require any dark matter, came from Milgrom[96] who proposed a modification of the theory of Newton dynamics. Nevertheless, MOND, this new theory, cannot at the same time explain Coma dynamics and the spiral rotation curves (The & White[132]).

5.2 Diffuse Light

Zwicky[167]'s original approach to the "missing mass" problem consisted in looking for the missing light. He was the first to claim detection of large luminous patches in the centre of Coma. Later on, Welch & Sastry[150], Kormendy & Bahcall[82], Thuan & Kormendy[136] and Mattila[90] also found evidence for diffuse light in the centre of Coma. The contribution of this diffuse component to the total cluster mass was however estimated to be negligible (at most 3 % of the total mass, according to Kormendy & Bahcall).

Mattila proposed several possible origins for this diffuse light: extended galaxy envelopes, dwarf galaxies (see § 4), globular clusters, intergalactic stars, scattering by dust grains (see § 5.4).

Recently, based on deep CCD observations, Bernstein et al. showed that the diffuse light in Coma follows the same distribution of globular clusters and

dwarf galaxies, and the units that make up such a diffuse luminosity must be $\leq 10^3 L_\odot$.

5.3 Diffuse Gas

As early as in 1956, the first detection of IC gas was claimed by Heeschen[66], based on 21-cm line-emission observations. Heeschen concluded that the total mass in HI was $\sim 1/4$ of the total cluster mass. However, his result was shown to be spurious by Muller[98].

Boldt et al.[17] first claimed detection of extended X-ray emission in the direction of Coma, but this finding was shown to be inconsistent with other observations (Friedman & Byram[48]).

In 1970 Turnrose & Rood[142] used the available Hβ and X-ray data to set an upper limit of 10^5 K to the temperature of a diffuse gas with the mass needed to bind the cluster. Their work was published shortly before the real detection of Coma in the X-ray by Meekins et al. and Gursky et al. (see Fig.10). Assuming that the emission was thermal bremsstrahlung from an IC gas, Gursky et al. estimated its mass in a few percent only of the total cluster mass.

The detection of the Fe line with *OSO-8* by Serlemitsos et al.[121], proved the thermal nature of the X-ray emission. At the same time, the presence of metals in the IC gas indicated that this had been at least partly processed in stars.

Currently, the contribution of the hot gas to the total mass is known to increase with the distance from the cluster centre, possibly up to $\sim$ 50 % (Hughes). A cool diffuse gas component may have now been detected (Lieu, these proceedings).

5.4 Diffuse Dust

Zwicky[168] noted a deficiency of clusters behind the Coma cluster as compared to other regions of the sky. He interpreted this deficiency as evidence for IC extinction, presumably due to diffuse dust. Later, Noonan[101] found evidence for IC extinction of ~ 0.4 mag in the blue band, in agreement with the estimate given by Karachentsev & Lipovetskii[77]. Few years later, Wesson[151] made the rather extreme hypothesis that IC dust may be present in such large quantities as to bind the Coma cluster!

The IC dust hypothesis encountered more criticism than consensus. In the 60's de Vaucouleurs noted that the fact that diffuse gas remained undetected implied a low density of diffuse dust, and Abell[4] considered the evidence for IC inconclusive. Smart[125] showed that IC dust must be significantly depleted

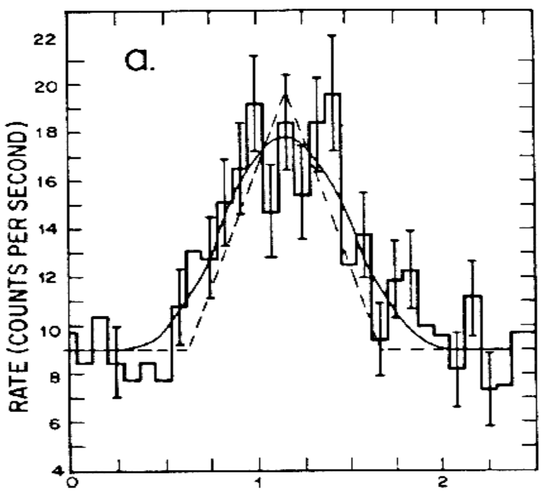

Figure 10: The counting-rate distribution vs. the relative azimuth (in degrees) obtained with the *Uhuru* instrument in the direction of Coma; the solid line shows a fit to the data with an extended source model, while the dashed line shows the expected distribution for a point source – from Gursky et al.

because of the dust grain sputtering by the hot IC gas. Tifft & Gregory[138] identified a group in the background of Coma and showed that the magnitudes of galaxies in this group are not significantly affected by extinction.

Recently, Dwek et al.[41] modelled the formation and evolution of IC dust in Coma, including sputtering from the IC gas and dust injection from galaxies. They derived a dust density much below that required to explain the observed visual extinction, but consistent with the upper limit reported by *IRAS* for IR emission in the Coma region. Ferguson[46], using the Mg_2–(B-V) relation for Coma ellipticals, set an upper limit of E(B-V) ~ 0.05 for IC extinction.

The amount of IC dust recently detected with *ISO* (Stickel, these proceedings) is even lower than what predicted by Dwek et al.'s model.

5.5 Galaxy Halos

Ostriker & Peebles[105] suggested that the existence of massive halos around spiral galaxies was needed in order for the disks to be stable against bar formation. Their paper led Lecar[84] to suggest that the diffuse dark matter in Coma comes from tidally torn-off halos. Indeed, the lack of significant luminosity segregation of Coma galaxies may indicate that they have lost their

massive halos very early in the history of the cluster (see § 6.1).

Support to his model came from the observations of Thompson[134], who showed that the density of barred galaxies is higher in the cluster centre, as predicted if these galaxies have indeed lost their halos.

Lecar's hypothesis would imply similar mass-to-light ratios for galaxies and clusters, and this is consistent with current estimates (e.g. Bahcall[11]).

5.6 Particles

Most today's cosmologists think that dark matter is made of some sort of weakly interacting massive particles filling the Universe. Massive neutrinos have long been considered as possible candidates. Cowsik & McClelland[30] were the first to draw the attention of the astrophysical community to massive neutrinos. Their work is of relevance here, as they compared their model to the observations of Coma. In their acknowledgments, we can read:

> *Our interest in the problem of the Coma cluster started after listening to the excellent seminars on the subject by Professors Ivan R. King, Eugene D. Commins, and Joseph Silk.*

6 The Tidy Coma: A Place for Each Galaxy

When we say that Coma is a cluster of galaxies, we better specify the kind of galaxies we are speaking of. In fact, galaxies of different type and luminosity have different distributions in the Coma cluster, and the cluster looks different when only, say, the ellipticals, or the spirals are selected. Here I review the history of the discovery of galaxy segregation in the Coma cluster.

6.1 Luminosity segregation

Zwicky[169] was the first to notice that bright and faint galaxies in Coma have different radial distribution, bright galaxies being more concentrated. His finding was at odd with the conclusion reached by Omer[102] few years before. In the 60's the evidence for luminosity segregation had less supporters (Reaves[109]) than opponents (Abell[1] and Omer[103]), until the new data-set of Rood allowed Rood & Turnrose[116] to conclude that dwarfs are indeed less concentrated than bright galaxies (see Fig.11). Their results were confirmed by Noonan[101].

However, the luminosity segregation in Coma is not a very strong effect. Rood[110] and White[155,156] noted that a much stronger effect would result from two-body relaxation if all the cluster dark mass was in galaxy halos.

Using the new data-set of Godwin & Peach, Capelato et al.[23] showed that luminosity segregation is a more complicated issue than previously thought.

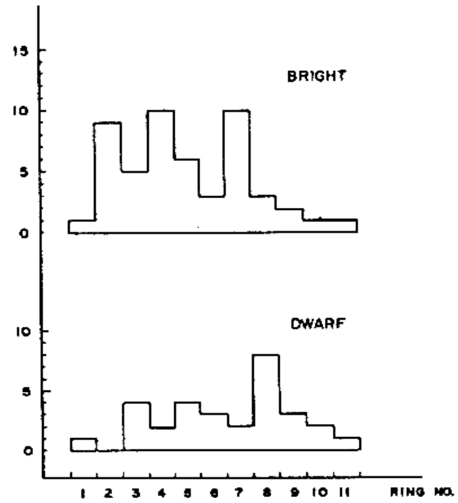

Figure 11: Bright and dwarf galaxy distributions in concentric rings centered on the Coma cluster centre. The ring no. increases with clustercentric distance – from Rood & Turnrose

While dynamical friction tends to produce a concentration of brighter galaxies in the Coma centre, merging of these same galaxies tends to reduce the number of intermediate brightness galaxies, and to create ultra-bright galaxies. Observationally, this effect is seen as an anti-segregation of galaxies with $m_{25} \leq 14.5$. Capelato et al.'s observational evidence was reproduced in Roos & Aarseth's numerical simulations only two years later (see also Athanassoula, these proceedings).

Thompson & Gregory showed that, among the dwarf galaxies, dwarf ellipticals follow the same distribution of giant ellipticals, while dwarf spheroidals are lacking in the core. This was interpreted as evidence for tidal disruption of the spheroidal galaxies (see also Secker, these proceedings).

Recently, Biviano et al.[16] showed that faint galaxies describe a more regular cluster than do bright galaxies, for which the effect of subclustering is stronger, and interpreted this finding as evidence for ongoing accretion of groups onto the cluster (see also § 7 and Lobo, these proceedings).

6.2 Spirals in Coma?

> *The fact that nebulæ near the centre of concentrated clusters are predominantly of the elliptic type, whereas spirals are relatively*

more numerous on the outskirts of clusters ...

... was already well known at the time Zwicky[164] was writing these lines, even if, in 1962, Neyman et al.[100] maintained that most (if not all) of this effect was due to an observational bias. Although Andreon[7] has recently shown they were not completely wrong, morphological segregation *is* real, and it can be seen in Coma as in (almost) any other cluster (being particularly evident when galaxies are selected in the UV, see Donas et al.[38]).

In this respect, what distinguishes Coma from most other clusters, is the almost complete absence of spirals. Abell[4] maintained there are no spirals in Coma at all, in contrast with Rood[111] and Rood et al. who found that some peculiar spirals do belong to Coma, and that at least 16 of the spectroscopically confirmed members of Coma were spirals or irregulars. Faced to the evidence that some spirals have velocities close to the mean cluster velocity, Abell[5] made the hypothesis that these spirals are members not of the cluster but of the Coma supercluster.

Sullivan & Johnson[129] observed three spirals in Coma and found that they had a surprisingly low HI abundance for their luminosity, when compared to similar spirals in the field, i.e. they were "HI-deficient". The authors concluded that these spirals have passed through Coma and have been stripped of part of their gas. Following studies (Sullivan et al.[128], Chincarini et al.[26], Bothun et al.[18], Gavazzi et al.[53]) not only confirmed these results, but also showed that the HI-deficiency mostly concerns spirals in the core of Coma, and not spirals in the Coma supercluster. This definitely proved the existence of a population of cluster spirals (note however that Coma spirals are *not* H_2-deficient, see Boselli, these proceedings).

Doi et al.[37], via automatic classification of galaxy types, have recently concluded that the spiral fraction in Coma was previously underestimated (see also the contribution of Andreon in these proceedings).

Note that, even if spirals are cluster members, dwarf irregulars are not (Thompson & Gregory).

6.3 Velocity Segregation

Different galaxies in Coma have different velocity distributions. This was first noticed by Hawkins[65] who pointed out that galaxies in the Coma centre have a lower mean velocity than galaxies at the edge. However, the value he quoted for the central galaxies (6254 km/s) was very low, and has never been confirmed since.

The first firm result on the velocity segregation in Coma was obtained by Rood et al. These authors noticed that the five brightest galaxies ($m_p < 15.0$)

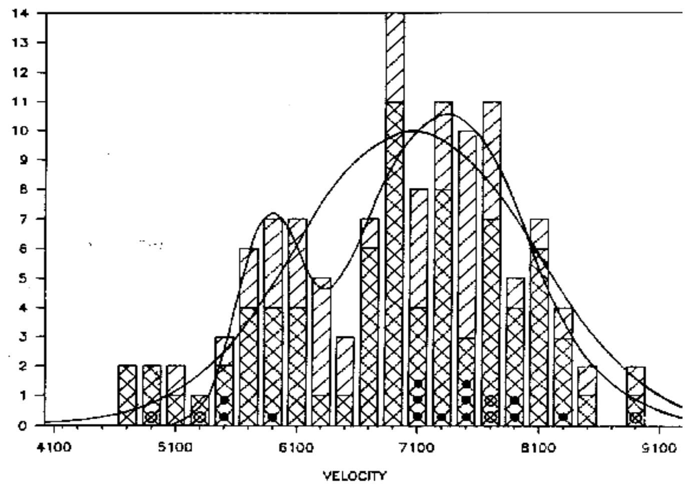

Figure 12: Histogram of velocities (in km/s) within 1° of the centre of Coma (shaded) and within 0.5° of Coma (double shaded); strongly HI-deficient galaxies (filled circles), and moderate or null HI-deficient galaxies (open circles), are shown. Curves represent Gaussian fittings to the data – from Gavazzi

of the Coma core have a very low velocity dispersion, $\sigma_v = 231$ km/s. Such an evidence was first confirmed by Struble[127] and more recently by Mellier et al. Struble considered two possible explanations to this effect: (i) the existence of a subcluster in the Coma core, and (ii) the result of dynamical friction (see also § 7.2).

In the early 70's, Tifft and des Forêts & Schneider[35] noted that Coma ellipticals have a different mean velocity from non-ellipticals. Ten years after, Kent & Gunn showed that σ_v increases along the Hubble sequence, from ellipticals to S0s to spirals. This was recently confirmed in the works of Andreon[8], Biviano et al.[16], and Colless & Dunn. Zabludoff & Franx[161] compared the whole distributions (not only their moments) of different morphological types, and found that the velocity distributions of ellipticals and spirals are different.

There is a general agreement in interpreting these results as evidence that the blue/star-forming galaxies have not yet reached virial equilibrium, and are still infalling into the cluster (some of them possibly for the first time).

What remains possibly unexplained is the double-peaked velocity distribution characteristic of many populations of Coma galaxies (see Fig.12):

- supercluster spirals (Gavazzi[52]);

- HI-deficient galaxies (Gavazzi[52]);
- post-starburst galaxies (Caldwell et al.[22], see Fig.16 in Biviano et al.[16]);
- UV-selected galaxies (Donas et al.[39]);
- radio-galaxies (Kim et al.[79]);
- S0 galaxies (Zabludoff & Franx);
- blue galaxies (Biviano et al.[16]).

Of the two peaks, one is centered at $\sim$ 7500 km/s (close to the mean velocity of the SW group, see § 7.1), and the other is centered at $\sim$ 5500 km/s, while the cluster mean velocity is $\sim$ 6900 km/s. Subclustering would seem the most obvious explanation for this complex velocity distribution, yet galaxies with velocities close to these peaks are not spatially subclustered (see also Gerbal, these proceedings).

7 Slicing Coma

Coma has long been considered the prototype of well-relaxed, regular clusters (see § 1). Nevertheless, also the existence of substructures in Coma has long been known. This is shown in the next sections.

7.1 The SW Group

The existence of a subcluster at $\sim 0.5°$ South-West of the Coma centre, around the bright galaxy NGC 4839, was already noticeable in the map of the density of nebulæ in the Coma region (see Fig.2), that Wolf made in 1902. The presence of the SW galaxy concentration was confirmed by Shane & Wirtanen's galaxy counts, half a century later (see Fig.13). Here is how Shane & Wirtanen described the SW subcluster:

> *It is apparent that there is a subsidiary concentration of nebulæ southwest of the cluster center. This grouping may be a secondary feature of the cluster or it may represent an independent aggregation.*

Note that Wolf's map was not mentioned in Shane & Wirtanen's paper.

Following up Shane & Wirtanen's "discovery" of the SW subcluster, van den Bergh[145] developed the first objective method for the detection of subclustering. He measured the apparent galaxy separations in Coma, before and after scrambling the galaxy position angles, while keeping their clustercentric

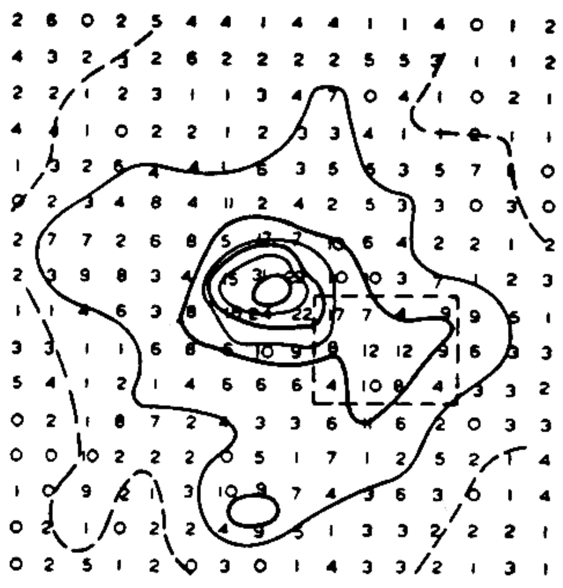

Figure 13: The density of nebulæ in the region of Coma, according to Shane & Wirtanen. Note the south-western extension, indicated by dashed lines (north is up, east is to the left).

radial distances unchanged. He found that the apparent galaxy separations were smaller in the real cluster than in the synthetic one, and concluded:

> *Taken at face value, this result implies that subclustering occurs in the Coma cluster.*

His result motivated Abell[2,3] to perform his own analysis of substructure. He found evidence for subclustering in 5 out of the 7 clusters examined, but not in Coma.

Omer et al. built the Coma density profile, based on three independent galaxy counts in the Coma region, and found a clear secondary peak at 0.5° radial distance.

The apparent overall regularity of Coma led Rood & Turnrose to suggest, by analogy, that the SW concentration was rather a background group than a subcluster.

In the 70's the first X-ray maps of Coma (Gorenstein et al.[59] and Johnson et al.[75]) were produced. The limited size of these first X-ray maps did not allow the detection of the SW group. Nevertheless, a SW extension *was* visible

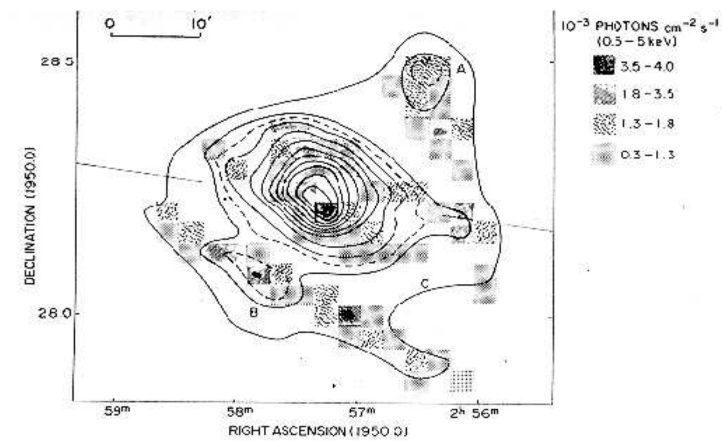

Figure 14: The map of the X-ray emission from Coma in the 0.5-5 keV band – from Johnson et al.

in the map of Johnson et al. (see Fig.14).

In the 80's the SW group was finally identified also in the velocity space. Baier[12] reported[h] on Sherbanowsky[123]'s identification of a group of 12 galaxies with an average velocity of 7437 km/s in the SW of Coma. Sherbanowsky's estimate for the mean velocity of the SW group was only $\sim$ 100 km/s higher than the current estimate[i].

Another (independent) detection of the SW group in the phase-space came from Perea et al.[108] Their estimates of the average velocity and σ_v of the SW group, were however offset by 200 km/s from current ones[27].

In spite of all previous evidences on the existence of a SW subcluster, in 1988 Dressler & Shectman[40] claimed $\leq$ 6 % probability that Coma had substructures! In the same year, however, Mellier et al. published their seminal paper, in which they identified *"not less than 9 local density peaks",* including the SW group. Their estimates of the SW velocity moments were nevertheless based on 4 galaxies only, and therefore rather uncertain. Escalera et al.[42] put Mellier et al.'s results on a firm statistical basis, using the wavelet method for structure detection.

[h] Sherbanowsky's paper is extremely difficult (impossible?) to find even in very good libraries. It would have probably remained unnoticed, had Baier not mentioned it.

[i] Colless & Dunn estimate a mean velocity of the SW group of 7339 km/s and a velocity dispersion of 329 km/s

In the 90's the group around NGC 4839 was also discovered in the X-rays, first by Briel et al. using the *ROSAT PSPC,* and almost at the same time by Watt et al. using the *SL2 XRT.*

In the last years, the emphasis moved from the determination of the SW group properties to the determination of its evolution in relation to Coma. Has the group already passed through Coma, or is it infalling into the cluster for the first time? Both in the X-ray (White et al.[157]) and in the radio (Cordey[28]) there is evidence for a tail of gas behind NGC 4839, in the opposite direction to the cluster centre, as if the galaxy was falling into the Coma core, and its gaseous atmosphere was swept away by motion through an external medium. On the other hand, Burns et al.[21]'s numerical simulations suggest that the group has already passed through the cluster core[j].

The issue is still controversial (see Colless & Dunn vs. Biviano et al.[16]). Evidences in favour of the "first infall" scenario are:

- the X-ray and radio tail of NGC 4839;
- spiral galaxies in the SW group region do not show HI-deficiency (Bravo, these proceedings);
- the group properties (richness, velocity dispersion, X-ray luminosity), are all consistent with a non-perturbed group (Colless, these proceedgins).

Nevertheless, this scenario cannot explain the presence of a bridge of material connecting Coma and the group, detected as diffuse optical light (Mattila), as a spray of post-starburst galaxies (Caldwell et al., and Caldwell's contribution in these proceedings), in the X-ray (Briel et al.) and in the radio (Kim et al.[80]). If the group has crossed the cluster, this bridge could be interpreted as tidally stripped material from the group. The bridge is unlikely to be related to the filament connecting Coma to A1367 (see, e.g., West, these proceedings) since the filament orientation is different from that of the bridge. On the other hand, the North-East filament of the Coma supercluster has the correct orientation. Several groups are found to lie in this filament, and these are predicted to fall into the cluster in the future (West, these proceedings).

This issue could be solved by an accurate determination of the relative distances between Coma and the group, via the use of secondary distance indicators (see the preliminary results of Lima-Neto in these proceedings).

[j] In their paper Burns et al. note that *"the recession velocity of the NGC 4839 group is slightly smaller (by $\sim$ 100 km s^{-1}) than that of the Coma cluster".* This is wrong, the recession velocity of the group is $\sim$ 400 km/s *higher* than that of Coma.

7.2 Subclusters in the Core

The existence of substructure within the core of Coma was first suggested by Bahcall[10] in the 70's. She observed an anisotropic distribution of the bright galaxies in the Coma core, along the E-W direction and suggested that:

> *...the observed anisotropy of the bright galaxies could arise from subclustering around each of the two supergiants at the center of the cluster.*

She also noticed that subclustering was stronger around NGC 4874, the less bright of the two central dominant galaxies. Recent results[16,27] confirm her early suggestions.

One year later, Rood[114] pointed out *"a possible tendency for S0 galaxies to surround NGC 4874 and ellipticals to surround NGC 4889".* To my knowledge, there has been no confirmation of this effect. The recent morphological catalogue of Andreon et al.[9] is best suited for the investigation of this issue (see also Andreon, these proceedings).

In January 1979 two papers appeared, both fundamental for the understanding of subclustering in the Coma core, one from Quintana[107], the other from Struble.

Quintana noticed a narrow density peak centered very close to NGC 4874, and suggested it *"may indicate the presence of a dynamically separated subunit".* Struble observed that the velocity dispersion of three clusters (among which Coma) decreases when only the core region is selected. This was interpreted as evidence that

> *...the most massive galaxies in the core have "captured" less massive galaxies as satellites and formed isolated subsystems*

Struble also mentioned dynamical friction as a possible alternative explanation (see § 6.3).

Valtonen & Byrd's binary model for the Coma cluster (see § 3.3) was motivated by the growing evidence of the existence of subclusters in the Coma core. This suggests that by the late 70's the idea of a complex structure for the Coma core was already taking root in the astrophysical community. In 1984, Baier published the first paper specifically devoted to the issue of subclustering in Coma. He reviewed the evidence for subclustering in Coma, partly coming from the presence of the SW-group (see § 7.1), and partly from the *"double character of the central cluster region".*

The evidence for subclustering in the Coma core was growing fast. Perea et al. first identified the two central groups in velocity space, and found mean

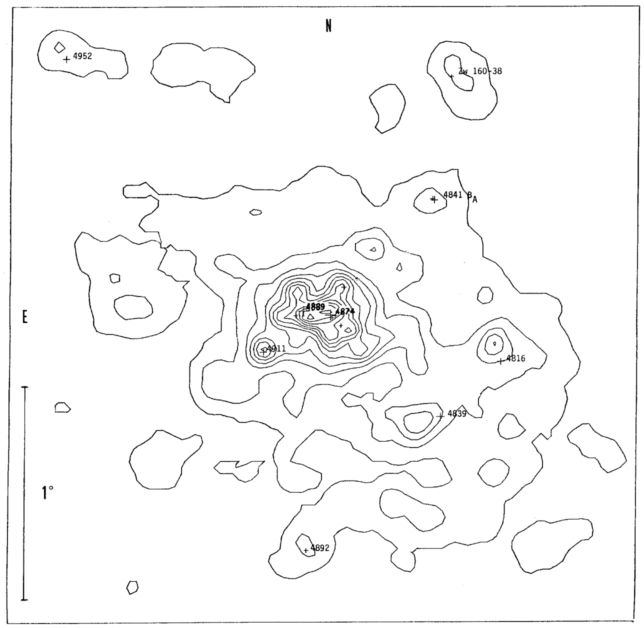

Figure 15: Isocontours of galaxy number densities in the Coma cluster; the brightest Coma galaxies are listed. The vertical line on the left indicates a scale of 1° – from Mellier et al.

velocities of 6431 km/s and 7072 km/s, and velocity dispersions of 220 km/s and 137 km/s for the groups centered around NGC 4889 and NGC 4874, respectively. Their results anticipated those of Fitchett & Webster and Mellier et al., both qualitatively and quantitatively (Mellier et al.'s estimates of the velocity moments of the two central groups differ by less than 10 % from Perea et al.'s), yet Perea et al.'s paper received much less attention than the other two[k] (was the word "taxonomical" in the title of their paper weird enough to discourage potential readers?).

Fitchett & Webster were possibly the first to use the word "substructure" in the title of a paper on Coma. Using the Lee-method, they separated galaxy members of the NGC 4889 group from galaxy members of the NGC 4874 group, and proposed a circular-orbit dynamical model for the two central subgroups (reminiscent of Valtonen & Byrd's model). They mentioned two possible ori-

[k] The *NASA Astrophysics Data System* lists only three papers making reference to Perea et al., as compared to 75 papers referring to Fitchett & Webster and 43 papers to Mellier et al.

gins for the substructures in the core:

1. Coma is presently forming by the merger of two large subunits;
2. the two substructures in the Coma core were independent groups that have fallen into a pre-existent cluster.

Nowadays, a third interpretation[27] has made his way:

3. NGC 4874 is the original dominant galaxy of the cluster, that has recently suffered from a collision with a small group centered on NGC 4889.

The difference between the NGC 4874 velocity and the mean cluster velocity (as well as its radio-morphology, see below), still gives some credit to Fitchett & Webster's scenario n.2 (see Biviano et al.[16]).

Of the 9 density peaks identified by Mellier et al. in Coma, two of them are in the cluster core (see Fig.15), centered on NGC 4889 and NGC 4874, that are surrounded by a population of satellite galaxies. In Mellier et al.'s scenario, these subclusters exist as independent groups before infalling into the cluster. At the time of infall, they have already passed through a mass-segregation instability-phase. During the infall, tidal effects strip the groups of their less bound low-mass galaxies, while the high-mass galaxies in the group cores, resist longer. Support from their scenario came recently from Biviano et al.[16], who showed that faint galaxies ($b \geq 17$) do not cluster around the giant galaxies, at variance with bright galaxies.

Mellier et al. estimated masses of $6 \times 10^{13} M_{\odot}$ and $5 \times 10^{13} M_{\odot}$, for the groups around NGC 4874 and NGC 4889, respectively. Their estimates have since been confirmed (to within 50 %) by later works (see below).

Some years later, Escalera et al.'s wavelet analysis detected the two central substructures with 99.9 % significance. The velocity dispersions they derived for the two subclusters are rather high, and more similar to the values found by Fitchett & Webster than to those found by Perea et al. and Mellier et al. Probably, contamination by cluster (and not group) members, affected their σ_v-estimates.

Non-optical wavelength observations also provided evidence for for a complex structure of the Coma core. In 1985, Feretti & Giovannini[45]'s radio observations of NGC 4874 showed that this galaxy was a Wide-Angle-Tail radio-source. This morphology is indicative of motion of NGC 4874 through the surrounding IC gas, i.e. the galaxy is not at rest at the bottom of the cluster potential (or the IC gas has a bulk velocity).

Based on the radio morphology of another galaxy in the Coma core, NGC 4869, whose radio-emission was first mapped by Willson, Feretti et al.[44]

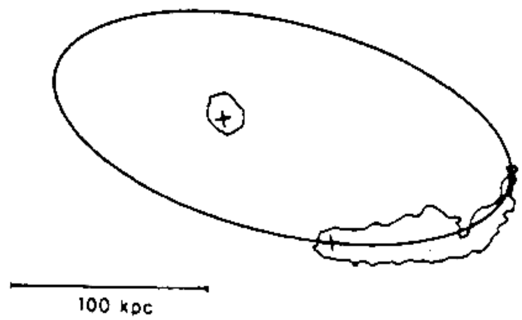

Figure 16: The orbit of NGC 4869 around NGC 4874 as derived by Feretti et al. The radio-morphologies of the two galaxies are sketched.

obtained the orbit of this galaxy around NGC 4874 (see Fig.16), and estimated the mass of the couple in $5 \times 10^{13} M_{\odot}$ (similar to Mellier et al.'s estimate).

Last came the X-ray observations. In 1993 Davis & Mushotzky[33] and White et al. detected substructures in the X-ray image of Coma. In particular, Davis & Mushotzky[l] used the *Einstein* data to show the existence of excess X-ray emission from NGC 4874, and a region 2.5' west of NGC 4889. The higher resolution *ROSAT* data allowed White et al. to confirm the former detection, but not the latter. Other irregularities in the X-ray surface brightness were found, all associated with bright galaxies, NGC 4889, NGC 4911, NGC 4848 and NGC 4839 (this last already mentioned in § 7.1). The groups detected by Mellier et al. in the optical were showing up in X-rays!

White et al. also detected a secondary peak of emission, half-way between the two central dominant galaxies, which they interpreted as gas stripped off NGC 4889. Biviano et al.[16] found an intriguing positional coincidence of this X-ray peak and the number density peak of faint Coma galaxies. They suggested that White et al.'s secondary peak is in fact emission from the main body of the Coma cluster, masked by the superposition of several subclusters.

[l] When Davis & Mushotzky first found evidence for substructure in the core of Coma *in the X-ray,* this was known in the *optical* since 20 years[10]. In perspective, the following statement of them sounds auto-ironic:

> *The ability of the x-ray observations to locate this structure when both galaxy counts and radial velocity information were inconclusive [...] is an indication of the power of searching for substructure in x-rays.*

Finally, Vikhlinin et al.[147] applied the wavelet analysis to the *ROSAT* image of Coma, disentangling the emission of the two central groups from that of the cluster. The optical[42] and X-ray wavelet-images looked remarkably similar. Under quite general assumptions, they were able to estimate the masses of the NGC 4874 and NGC 4889 subclusters in $3.4 \times 10^{13} M_{\odot}$ and $2.6 \times 10^{13} M_{\odot}$, again quite close to the original Mellier et al.'s estimates.

7.3 The Radio Halo Coma C

A complete history of the Coma structure would not be complete without mentioning the radio-halo of Coma. In fact, theory and observations suggest that it is related to the subclustering in Coma.

Cluster radio-halos are very rare; Hanisch[64] searched for Coma-like radio-halos in 72 nearby Abell clusters and did not find any! So, Coma is rather exceptional in this respect (there are only ~ 10 cluster radio-halos known, see Feretti, these proceedings). Its radio-halo, Coma C, was first detected at 408 MHz by Large et al.[83], as an extended source of 45' size at the Coma centre. Willson showed that Coma C could not be produced by the integrated radiation from normal galaxies. Kim et al.[80] and Venturi et al.[146] found that Coma C extends to the SW, and Giovannini et al.[56] proposed the existence of a unique source extending from Coma C to 1253+274, passing through the SW group around NGC 4839 (see § 7.1). Recently, Feretti et al.[43] measured a magnetic field associated with the cluster of $\sim 8.5\mu$G, tangled on scales ≤ 1 kpc.

The theorists had trouble in explaining the energy source of Coma C (see, e.g., Tribble[139]). The radio-halo can be powered by relativistic electrons moving in a magnetic field. Cluster radio-galaxies can provide the relativistic electrons, but the strength of the magnetic field and the large extent of the radio-halo imply that the electrons must be re-accelerated far from their sources.

In the currently best model, recent ($\sim 10^8$ years) subcluster collisions provide the re-acceleration energy (see Tribble[140]). However, many clusters contain substructures, and only a few clusters contain radio-halos, so the situation is not so simple (see Feretti's contribution in these proceedings for a discussion on this topic).

8 An Old Vision of a New Cluster: Summary and Conclusions

At the end of this long yet not exhaustive historical review, one is left with the feeling that everything was already known since long ago. It is sufficient to have a quick look to the important steps in our scientific understanding of the Coma cluster, before 1980:

- 1901: Wolf gives a map of Coma in which the SW group is already clearly visible;
- 1937: Zwicky discovers the "missing-mass" problem;
- 1954: Shane & Wirtanen's galaxy counts also show very clearly the SW subcluster;
- 1957: Zwicky finds that bright and faint galaxies have different radial distributions;
- 1958: Zwicky shows that the "missing-mass" problem is a "dark-matter" problem, because clusters are stable and non-expanding;
- 1959: Abell finds the secondary peak in the otherwise monotonically increasing luminosity function of Coma galaxies;
- 1959: Large et al. detect Coma C, the radio-halo, at 408 MHz;
- 1960: Mayall shows that the velocity dispersion decreases with increasing clustercentric distance;
- 1961: van den Bergh makes the first objective detection of subclustering in Coma;
- 1966: Reaves suggests that the lack of dwarf galaxies in the Coma core is due to tidal disruption;
- 1971: Meekins et al. discover the X-ray emitting IC gas in Coma;
- 1973: Bahcall suggests the existence of subclustering around each of the two central dominant galaxies;
- 1973: des Forêts & Schneider show that galaxies of different types have different velocity distributions;
- 1975: Lecar shows that the lack of significant luminosity segregation imply that cluster galaxies have lost their halos;
- 1978: Sullivan & Johnson find three HI-deficient spirals in Coma;
- 1979: Johnson et al.'s X-ray map of Coma hints at the presence of a SW extension.

At the time they were produced, many of these early results needed firm confirmation, that eventually came from more (and more accurate) data; on the other hand, our theoretical understanding of these observational evidences is still far from complete. However, it seems to me that the picture of a dynamically young Coma cluster was already contained in these early results. So, maybe a more appropriate choice for this conference title could have been: "An Old Vision of a New Cluster".

Acknowledgments

This paper is dedicated to my wife Patrizia, for sharing my busy life of wandering astronomer.

No historical review is unbiased. I apologize for the excessive emphasis I may have put on my personal results, and for all other people's results that I have misquoted or forgotten to mention.

I wish to thank Fabienne Casoli, Florence Durret, Daniel Gerbal, Alain Mazure, for the perfect organization of this conference. I thank Michael West for pointing out to me Herschel's work on the Coma cluster. I acknowledge the hospitality of the Trieste Astronomical Observatory, where a significant part of my bibliographic research was done.

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